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THE COGNITIVE ORGANIZATION OF SUBMARINE SONAR INFORMATION:

A Multidimensional Scaling Analysis

by

K. Laxar, G. Moeller and W. H. Rogers

Naval Medical Research and Development Command
Research Work Unit M0100.001-1015

Released by:
W. C. Milroy, CAPT, MC, USN
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SUMMARY PAGE

THE PROBLEM

To determine how sonar information is organized and assigned priorities by the Submarine Conning Officer, so that recommendations can be made regarding information displays of future submarine systems.

THE FINDINGS

Submarine Officers organize sonar information in two basic dimensions, related to the source of the information and to the destination of that information. The most important pieces of information were those at the ends of these dimensions, with a summary of sonar contact data rated most important, followed by such information as own ship data, raw visual sonar displays, and ocean acoustic parameters. Significant agreement was found among groups of officers of varying levels of submarine experience.

APPLICATION

If it is found that financial or information processing limitations restrict the amount of sonar information presented directly to the CONN, data on sonar contacts, own ship parameters, visual representation of raw sonar signals, and ocean acoustic parameters should be provided. All other data should be displayed, as now, in sonar.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of Naval Medical Research and Development Command Work Unit M0100.001-1015 -- Sonar human factors problems. The present report is Number 1 under this work unit. It was submitted for review on 29 September 1983, approved for publication on the same date and it has been designated as NSMRL Rpt. 1010.

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THE COGNITIVE ORGANIZATION OF SUBMARINE SONAR INFORMATION: A MULTIDIMENSIONAL SCALING ANALYSIS

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Summary -- Nonmetric multidimensional scaling (MDS) techniques were employed to determine how sonar information is organized and assigned priorities by the Submarine Conning Officer (CONN). Data were collected from 95 Submarine Officers with varying amounts of at-sea experience. All types of information proposed for display in modern sonar systems were classified by the investigators into 15 categories. Descriptions of the categories comprised the stimuli for the two tasks the subjects performed. In an unconstrained sorting task subjects sorted the 15 stimuli into groups according to similarity of the sonar information described, to provide data for the MDS analysis. In a ranking task, subjects rank ordered the stimuli according to importance at CONN. The MDS analysis provided evidence that the officers organize sonar information in two dimensions, related to Information Source and Information Destination, while the rank order data indicated that most importance was attached to the information at the extremes of these dimensions. Significant agreement was found among all subjects, regardless of experience level, in the way the sonar information was psychologically organized and prioritized.

Recent technological developments have made the human-machine interface increasingly complex in terms of the kind and amount of information available and how it is displayed. The Naval Submarine Medical Research Laboratory has addressed some of the resultant problems in the design and operation of automated information systems, in particular, submarine sonar systems. One phase of this project has been to identify those pieces of sonar information that are perceived by the Conning Officer (at the "CONN"), who is immediately in charge of ship operations, to be most useful in ship control. Current hardware makes it possible to display any or all sonar information at the CONN, from raw auditory data to refined visual displays of predicted ships' positions. Two important considerations, however, may dictate that less information be provided than is technologically possible. One of these is financial, in terms of hardware and software costs. The other, which this research addresses, is the limitation by human information processing capacities, since many information processing theorists consider too much information a source of performance degradation (e.g., [1]).

There exist a number of different approaches to identifying and prioritizing the sonar information that should be displayed at CONN, but each has its associated problems. It has been our experience, for example, that judgments by systems engineers frequently are not well received by the operational forces, and that simple polls of experienced submarine officers often yield equivocal results. More meaningful information, on the other hand, could be obtained by empirical assessment of alternatives during real or simulated operations, but such an approach can be expensive and time-consuming. In lieu of these approaches, Zachary [2] has employed nonmetric multidimensional scaling techniques [3]-[6] in the context of Naval Air antisubmarine warfare (ASW) in prioritizing decision-making situations. Such techniques have been applied in the present study to judgments about sonar information, to determine how such information is organized and assigned priorities by the submarine Conning Officer.

Method

Subjects

Data were collected from 95 Naval Officers in the New London area. In order of decreasing seniority and experience, the sample consisted of 11 Commanding Officers, 16 Executive Officers, and 30 junior men qualified as Officers of the Deck, from eight fast attack (SSN) and eight fleet ballistic missile (FBM) submarines. In addition, 38 junior officers, who had recently completed the Submarine Officer's Basic Course at the Naval Submarine School, participated. This last group, in general, had no at-sea experience.

Stimuli

The various types of information available from current and proposed sonar systems were classified by the investigators into 15 categories, as listed in Table I. Descriptions of these categories comprised the 15 stimuli for the tasks to be performed. Discussions with sonar instructors indicated that the selected categories were exhaustive of the types of sonar information that could be presented at CONN. Each of the stimuli was typed onto a separate card, numbered on the reverse side, to create the stimulus deck. A questionnaire administered after the data collection confirmed that the categories were meaningful and that no important piece of information had been omitted.

Procedure

To provide data for the multidimensional scaling analysis, subjects were first asked to perform an unconstrained sorting task, arranging the stimuli into as many or as few groups as they felt necessary, according to similarity. The definition of similarity was left up to the subject. Cards which described similar categories were to be placed in the same group, and any card which described a unique category was to be placed by itself. Then, to provide additional data for interpreting the scaling analyses, subjects were asked to rank order the stimuli according to importance at the CONN for two different operational missions. The first mission assumed an SSN on an ASW direct support patrol. In such a scenario, own ship would seek out and follow enemy submarines. The second mission assumed an FBM patrol in an area where a high density of sonar contacts was expected. In this scenario, own ship would remain in a designated area and try to avoid detection by enemy vessels. Subjects were instructed

then to mark their rank-ordered lists to show which options were necessary, merely desirable, or unnecessary. After each task, subjects recorded their data on answer sheets according to the code number on the back of each stimulus card.

Due to time constraints in obtaining data from these subjects, the sorting procedure was used in lieu of the pairwise judgment of similarity often employed in this type of analysis. Data were usually collected from small groups of subjects, such as one ship's crew, in sessions lasting approximately one hour.

Results and Discussion

The data from all subjects for the unconstrained sorting task were entered into a computer program which produced a dissimilarities matrix for the 15 stimuli, assigning values to the 105 pairs of stimuli according to the number of times subjects placed them in the same group. This initial procedure thus produced a proximities matrix from the nominal scale sorting data. The resultant matrix, in turn, was the input to the KYST-2A multidimensional scaling program [7]. Through this technique as employed here, a configuration of points (stimuli) in Euclidean space is constructed by an iterative adjustment process, based on the observed dissimilarity between all pairs of stimuli. The final configuration is then rotated so that the principal components of the points lie along the coordinate axes. The object of this procedure is to help determine the underlying psychological structure of the stimulus domain, namely the various pieces of sonar information.

TABLE I

The categories of sonar information that comprised the stimuli. The numbers indicate the aggregate rank ordering by importance, and the partitions indicate the degree of necessity, for all subjects.

Rank	Kind of Information	Necessity
1.	Contact Summary - Geographic	
2.	Contact Summary - Tabular	
3.	Single Contact Data	NECESSARY
4.	Tactical Aids	
5.	Own Ship Data	
6.	Contact's Active Sonar	
7.	Raw Visual Displays	
8.	Ocean Acoustic Parameters	
9.	Ranging Data	DESIRABLE
10.	Classification Aids	
11.	Environmental Parameters	
12.	Passive Sonar Setup	
13.	Raw Auditory Signals	
14.	Active Sonar Setup	UNNECESSARY
15.	Sonar Hardware Status	

The computer analysis was repeated with 10 different starting configurations to ensure that the obtained solution was a result of the stress value reaching a global, rather than a local, minimum.

The resulting two-dimensional solution is presented in Figure 1, with the number of dimensions selected according to the suggestions given by Shepard [8]. These included consideration of data values in the dissimilarities matrix, stress values for other dimensionalities, and meaningfulness in the interpretation of the axes.

The labeling of the dimensions in a multidimensional scaling configuration is, for the most part, based on the information available to the investigators about the set of stimuli being scaled. Examination of Figure 1 leads us to believe that, at least for the sorting data we obtained, the officers organize sonar information in terms of no more than two basic dimensions: data concerning sources of information, as shown along the vertical axis, and data related to the destination of that information, as given along the horizontal axis. The two extremes of the Information Source dimension are delimited by information from the world external to the submarine. At one end are auditory and visual displays of the relatively unprocessed sonar signals arriving at the ship's hyrdophone arrays, obtained in passive mode from noise generated by the sonar contact. Also here lies information about the contact derived from any active sonar transmission the contact makes. At the other end of the scale is information about the environment which bears on sonar performance, such as sea state, ocean depth, and computed parameters for the acoustic properties of the surrounding ocean area. Information about, and derived by, own ship lies between the outside world extrema. Hence, this axis can be labeled as Contact versus Environment.

The Information Destination axis is concerned with where in own ship, the submariner's inside world, the available information is directed. The axis is delimited at one end by factors relevant to the CONN, which influence the maneuvering of own ship: a table listing all contacts and their classification, such as friendly or hostile, surface or submerged; a geographic picture showing the positions of contacts in relation to own ship; and displays showing predicted future positions of contacts and the effects of trial maneuvers. At the other end of the dimension is information relevant to the sonar personnel: the status of own ship's sonar equipment (performance monitoring/fault location) and the current utilization of the various pieces of active and passive sonar equipment. This axis can therefore be labeled in terms of Sonar versus CONN.

The data of all four groups of subjects were aggregated for each ranking task according to importance, and the Kendall coefficients of concordance $\underline{W}$ [9] were computed to assess between-judge agreement. For both rankings, agreement was highly significant, as indicated by the chi-square test. For the situation in which the submarine was acting in an ASW support role, a coefficient of $\underline{W} = .46$ was obtained, $X^2(14, \underline{N} = 94) = 609.9$, $\underline{p} < .001$. For the FBM patrol situation, a coefficient of $\underline{W} = .44$ was obtained, $X^2(14, \underline{N} = 94) = 577.9$, $\underline{p} < .001$.

The rank order of importance for the 15 items of sonar information was determined from the sum of their ranks from all subjects. This ranking for the FBM patrol situation is given in Table I, with the partitions according to necessity indicated. The ranking for the ASW support role situation was identical except for a transposition of items ranked 13th and 14th, and

when both rankings were combined, the ranking was as shown in the table. The ordering and categorization of these stimuli according to their importance at CONN appears quite reasonable. Those items deemed necessary are exactly those important to maneuvering own ship: the location of sonar contacts in relation to own ship, the classification of each contact, and the motion of own ship. Those items ranked moderate in importance were described as desirable, or nice to have, but not absolutely necessary. These items appear to be ones which are less useful, in themselves, to CONN in operating own ship, but which may help evaluate the quality of information categorized as Necessary. In that regard, it is quite unexpected to find the visual displays of relatively unprocessed sonar signals to be ranked as high as seventh. This may indicate a tendency of CONN to "look over the shoulder" of those in Sonar, perhaps just to make sure Sonar is not missing any contacts. Finally, those items labeled as Unnecessary are those concerned with the operation of the sonar system, generally under the complete purview of the Sonar Supervisor.

The numbers in Figure 1 show this rank order written beside the labeled points on the two-dimensional scaling configuration. Those four items ranked most important to, and directly concerned with, the function of CONN, are located together at the appropriate end of the Information Destination dimension. These are followed by data about Own Ship and Contact's Active Sonar, both slightly removed from the CONN extremum and relatively distant from each other, in the directions of the ends of the Information Source dimension. The next two items in importance are very close to the extremes of the Information Source dimension, the Raw Visual Displays at the Contact end, and Ocean Acoustic Parameters at the Environment end. Those items ranked least important relate to the sonar equipment and are placed at the appropriate end of the Information Destination dimension.

It may be noted, however, that the ranking by importance follows, in some approximate manner, the arrangement of the stimuli as one proceeds along the Information Destination dimension from CONN to Sonar. To determine if this unidimensional ranking formed the underlying basis for the configuration given by the KYST-2A scaling, the program was run again using the rank order as the starting configuration for a one-dimensional solution. As with other hypothesized unidimensional starting configurations run previously, the stress value for the one-dimensional solution was not improved beyond the value originally obtained. This result further indicates that while a meaningful unidimensional ordering can be imposed on these stimuli, the underlying organization is yet two-dimensional. In addition, however, Information Destination is very likely the more salient of the two dimensions.

To determine if the four groups of officers had organized or ranked the sonar information differently, complete separate analyses as described above for all subjects were computed on the data from each group. In all cases, results indicate that a two-dimensional solution was most appropriate. The KYST-2A scaling configurations were very similar for all groups, with the stimulus points in slightly different positions in their respective quadrants from one group to another. The one exception was that the Executive Officers placed Own Ship Data closer to the Contact rather than the Environment end of the Information Source dimension.

As indicated by the significant coefficient of concordance given above for all subjects, rankings between groups were also rather similar, characterized for the most part by transpositions of adjacent stimuli from one group to another. The notable exceptions were that the Commanding Officers ranked the Raw Visual Displays second, in the Necessary category, and the recent graduates of Submarine School ranked that same information in the 12th position, in the Unnecessary category. Commanding Officers were perhaps reflecting the desire to monitor the raw data in order to confirm

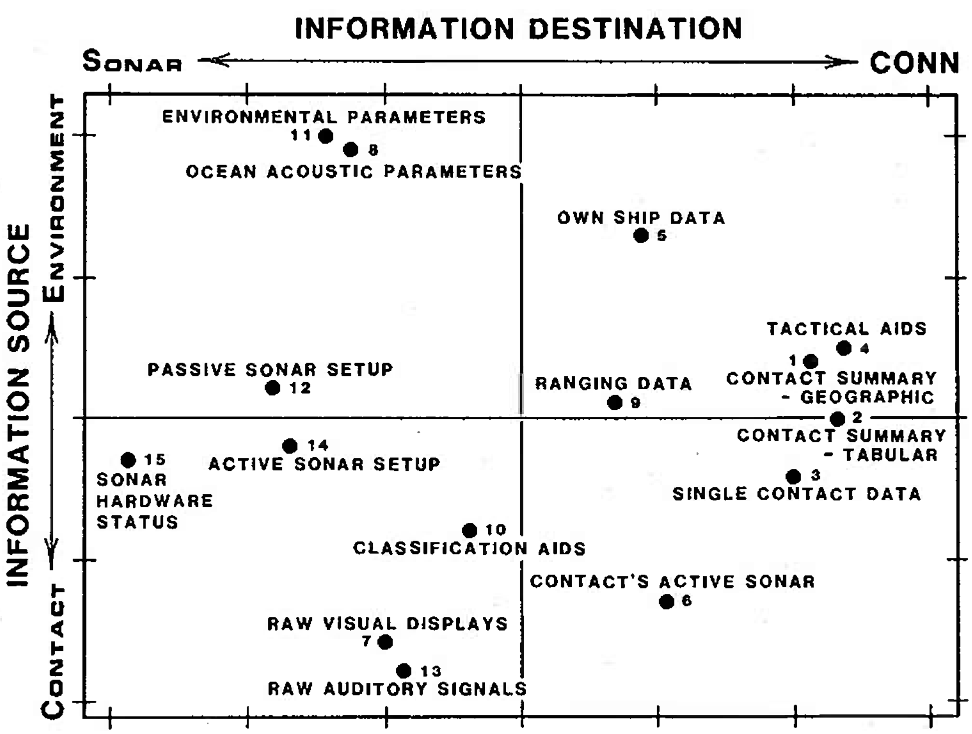

Figure 1. The two-dimensional solution for the KYST-2A scaling analysis, for all subjects. The numbers indicate the ranking by importance for the 15 categories of sonar information.

the accuracy of inferences represented by the categories, or to be closely involved with all phases of the ship's operation. The least experienced group, on the other hand, may have been expressing recently acquired training doctrine. Between-judge agreement for all groups was highly significant, with coefficients of concordance of $\underline{W}$ = .42 to .59 obtained. Within groups, as well, little difference was seen in rankings for the two different tactical missions.

When the rankings were compared between officers assigned to FBM submarines and those assigned to SSN ships, again, little difference was evident in the way the two groups ranked the stimuli for the two operational missions, and the rankings followed the same general pattern as presented in Table I. In addition to minor reversals in rankings between the two groups of officers, however, the FBM officers consistently ranked Own Ship Data as more important, third over all, than did the SSN officers, who ranked it seventh. This difference may reflect greater general concern on the part of the FBM officers with their ship being "on station," consistent with the mission of an FBM patrol. Similarly, SSN officers ranked Single Contact Data and Contact's Active Sonar two positions more important than the FBM officers did, possibly reflecting consistency with the SSN's mission. It should be noted that the differences between these groups are minimized by the fact that the officers could have had a varied range of experience on a submarine other than the type to which they were currently assigned.

The rankings for the groups of FBM and SSN submarine officers were combined with each other and across the two types of missions, as well. When compared with the ranking from the Submarine School graduates, the latter attached more importance to the Ocean Acoustic and Environmental Parameters and less importance to Own Ship Data and, as noted above, Raw Visual Displays. It is suggested that these differences may reflect experience gained at sea versus the aspects of ship operations emphasized in the Submarine Officer's Basic Course.

Summary and Conclusions

This study represents a successful application of the multidimensional scaling model, providing a representation of the way in which various pieces of sonar information are organized in the mind of the submarine Conning Officer. Results indicate that there is substantial agreement among officers of various levels of experience regarding the way the kinds of sonar information are organized. There is also agreement among these groups in the relative importance of these pieces of information in two different operational scenarios, both of which yielded similar rankings.

At least for the data obtained from unconstrained sorting by similarity, multidimensional scaling analyses suggest that two dimensions, at most, are required to describe the Conning Officers' conceptualization of the relations among various types of sonar information. One dimension is related to the source of available sonar information, whereas the orthogonal, and primary, dimension relates to where in own ship that information is directed or handled. The former dimension is laid out according to information from the sonar contact, from own ship, and from the ocean environment. The primary dimension involves sonar operations at one end and Conning Officer's responsibilities at the other.

When ranked according to importance, the information that the officers appear to require most is that from the extremes of the dimensional axes, except for that information directly concerned with the sonar hardware. For system design, these results suggest that data about the sonar system are least desired at CONN and hence could be omitted from the CONN's display if financial or information processing limitations dictate that all information should not be made available. If further restriction of kinds of data to be displayed at CONN were necessary, investigation of those types of information in closest proximity to each other in the multidimensional scaling solution, indicating highly similar data, would be appropriate to determine if there are any completely redundant displays. An hierarchical clustering analysis is underway to assess this redundancy.

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